Energy Policy 124 (2019) 111–122

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Challenges in greenhouse gas mitigation in developing countries: A case study of the Colombian transport sector

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ARTICLE INFO

Keywords:
CO_2 reduction
Climate change
Developing economies
Urban mobility
Freight transport
Co-benefits

ABSTRACT

CO_{2eq} emission scenarios for the Colombian transport sector were estimated for 2010–2050. We used a marginal abatement cost approach to assess an emission mitigation pathway. For this purpose, we constructed a carbon emission accounting model linking travel demand to vehicle stock, fuel consumption, and emissions for the Colombian transport sector. Actions related to energy efficiency, fuel switching, new engine technologies and modal change were considered. The analyzed measures have the potential to reduce the cumulative emissions by 8% and 18% under the BAU scenario through 2030 and 2050, respectively. Mitigation costs are high and imply annual capital costs that range from 0.5% to 4% of the national GDP. Gains in efficiency as well as synergy with other sector objectives might help justify some of the actions in financial terms. Non-technological actions, such as high public transit participation in the urban modal share and reorganization of the freight system, play a significant role in attaining low-carbon transport systems in Colombia.

1. Introduction

The average annual growth rate of global greenhouse gas (GHG) emissions from fossil fuel and industrial production increased to 2.3% during 2000–2015 from 1.3% during 1990–2000 (IPCC, 2014; Olivier et al., 2016). The highest contribution to total emissions has been shifting from developed countries to both emerging and developing economies. While net emissions from Annex I countries stagnated from 1990 to 2014, emissions from non-Annex I countries tripled during the same period (IEA, 2016).[1] In 2014, non-Annex I countries accounted for 58% of the global carbon dioxide equivalent (CO_{2eq}) emissions.

National climate action plans proposed by developed and developing countries at the 21st Conference of the Parties (COP21) reflect the agreement that in order to achieve a low-carbon world, mitigation needs to occur globally (IEA, 2016). Via its nationally determined contribution (NDC) presented to the United Nations Framework on Climate Change (UNFCCC) under the COP21, the Colombian government committed to reducing 20% of its GHG emissions under a business as usual (BAU) scenario by 2030 (UNFCCC, 2016). Even though the Colombian NDC does not establish sectoral goals, it does refer to transportation as one of the segments in which GHG mitigation must be pursued. This characteristic is common among COP21 commitments, in which 63% of the NDCs submitted in the representation of 187 countries included mitigation actions in the transport sector to comply with national goals (PSLCT, 2016).

The transport sector is critical in terms of its contribution to GHG emissions, and significant potential to mitigate GHG has been identified for this sector (Kahn Ribeiro et al., 2007). However, previous actions have shown the difficulty in achieving net emission reductions in transportation. In Europe, despite mitigation actions in place between 1990 and 2012, emissions generated by transportation continuously increased, and this trend was opposite than that observed for other emitting sectors (Santos, 2017). The difficulty in reducing GHG emissions in the transport sector can be attributed to several factors, including high capital costs, rebound effects, the absence of comprehensive policies that consider these types of indirect effects, and the lack of international legally binding agreements to reduce GHGs (Ajanovic and Haas, 2017; Druckman et al., 2011; Eliasson and Proost, 2015; Santos, 2017).

The wide range of local contexts and conditions among countries influence GHG emission patterns (IEA, 2016) and determine the feasibility of the mitigation options, by factors such as the institutional capacity (Zimmer et al., 2015). In this lies the importance of identifying the factors that drive emissions in each case and to find opportunities to reduce CO_{2eq} emissions in accordance with local circumstances.

The aim of our study is to assess GHG mitigation strategies in the

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[1] Annex I and non-Annex I countries as defined by the United Nations Framework Convention on Climate Change. Annex I parties are classified as industrialized, developed countries or economies in transition. Non-Annex I parties are primarily low-income and developing countries.

https://doi.org/10.1016/j.enpol.2018.09.039
Received 12 April 2018; Received in revised form 7 August 2018; Accepted 29 September 2018
Available online 09 October 2018
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Colombian transport sector in terms of their technical reduction potential and financial costs. This paper is structured as follows: Section 2 describes the main characteristics of the transport systems in Colombia; Section 3 explains the methodology used to conduct the analyses; Section 4 presents the main results regarding the costs and mitigation potential of the actions assessed and presents the lessons of the participatory approach; Section 5 discusses the consistency between GHG mitigation actions in the transport sector and other national objectives; and Section 6 concludes and presents the next steps.

2. Background information

The energy sector is the second contributor to GHG emissions in Colombia, after agriculture, forestry and other land use (AFOLU). The energy production contributes to a relatively small proportion of the national GHG emissions (9% in 2010 and 8% in 2012), due to the high share of hydropower, which represents nearly 70% of all electricity produced in recent years (UPME, 2015a). Transportation is the main contributor to energy-related CO_{2eq} emissions accounting for 10% of the national emissions inventory (22.6 Mt CO_{2eq} in 2010) (IDEAM, 2015). The road segment was responsible for 88% of the transportation emissions, whereas waterborne, aviation, and rail segments contributed 6%, 5% and 0.5%, respectively.

The transportation fleet increased from 6.3 million vehicles in 2010–12 million in 2015 (MT, 2017a, 2013), mainly determined by private transport demand. Despite the rapid growth of the fleet, aging vehicles lacking emission control technologies still characterize the fleet (MT, 2016). Due to obsolete technologies, public transit fleets, freight vehicles and motorcycles serve as important sources of local air pollution (GM, 2015; IDEAM, 2016; Rodríguez et al., 2016; SDA, 2010).

With respect to urban passenger transportation, public systems and non-motorized modes are the predominant alternatives for traveling. Conventional transit bus systems and bus rapid transit (BRT) systems are in place. The conventional type exists in all cities, while the BRT system exists only in the eight largest cities. Similar to other developing countries (Cuenot et al., 2012; Figueroa et al., 2013; Wang et al., 2017), a transition from public and non-motorized modes of transportation to private modes has been observed in recent years in urban areas in Colombia (Ipsos, 2016; Pojani and Stead, 2017). In particular, there has been a significant growth in the use of motorcycles. Currently, there are more motorcycles than passenger cars (MT, 2017a). To reduce transport externalities, a goal of the current government is for BRT systems and non-motorized modes to account for 40% of urban trips in the eight largest cities by 2018 (DNP, 2014a). In addition, taxis act as a complement to other modes; however, the growth of the taxi fleet is constrained by regulation (Rodríguez and Acevedo, 2012).

The high proportion of non-motorized trips and public transportation is related more to low income levels (Acevedo et al., 2009; Combs, 2017; Combs and Rodriguez, 2014) than to other factors, such as environmental awareness. Indicators such as the number of daily trips per capita, the proportion of transportation costs in relation to household income and other factors related to affordability and accessibility (Bocarejo S. and Oviedo H, 2012) indicate that many people in Colombian cities still face transport poverty. Low travel demand, high proportion of public transport and non-motorized modes translate into low carbon emissions per capita with respect to urban transportation.

Regarding freight transportation, more than 95% of goods in the country are transported by trucks (MT, 2017a). Notable exceptions include crude oil and coal (both for exporting), which have exclusive transportation infrastructure: oil pipelines and railway (Roda and Perdomo, 2011). High costs derived from a suboptimal logistic system have been reported (Anif, 2017; DNP, 2015a, 2013). Existing efforts to improve this sector include a program aimed at reducing the total size of the fleet; financial incentives to retire old vehicles would exist (DNP, 2014a). Additionally, the implementation of national platforms and multimodal projects have been prioritized and are currently in the planning phase (Anif, 2017; MT, 2017b).

In terms of energy demand, road cargo is the segment that uses the most energy; this segment accounted for 54% of all the energy demanded by road transportation in 2012 (UPME, 2014). Most light-duty vehicles are gasoline powered, whereas heavy-duty vehicles, including buses and trucks, run on diesel. The share of other energy carriers such as natural gas and electricity is small, representing 5% of the final energy consumption in 2012 (UPME, 2015b). Diesel fuel is blended with palm oil biodiesel (8–10%) and gasoline is mixed with sugarcane ethanol (8–10%) (CREG, 2015).

3. Methodology

We constructed a carbon emission model that accounted for the Colombian transport sector defined at the national scale; the model linked travel demand to vehicle stock, fuel consumption, and emissions (Fig. 1). Using a scenario analysis approach, we assess different mitigation options, and by comparing the results to those of a baseline

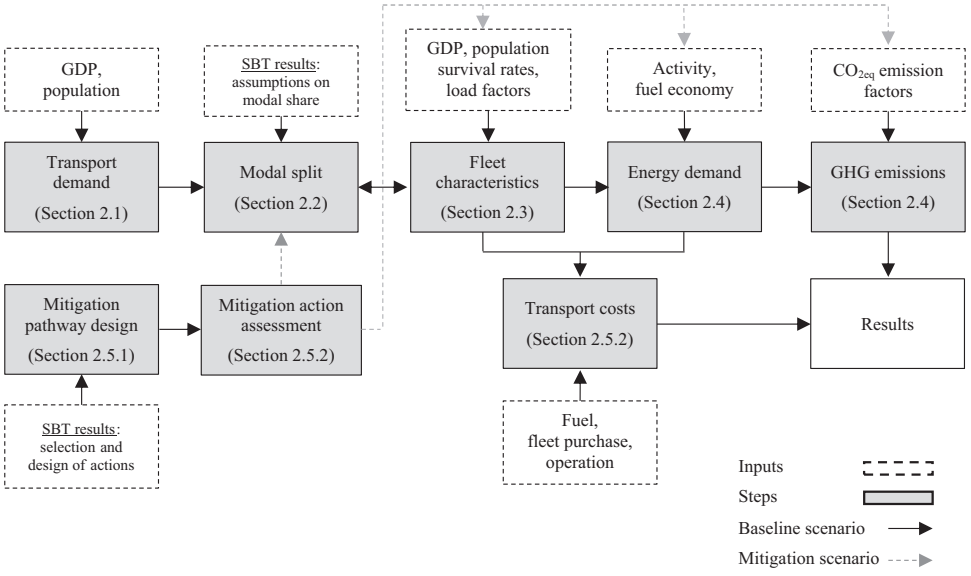

Fig. 1. Model structure. SBT: Scenario building team meetings. GDP: Gross domestic product. Adapted from Wang et al. (2017).

Table 1
Transportation categories included in this study.

Segment	Type of service	Scale	Modes	Type of vehicles
Road	Passenger	Urban	Private	Light-duty vehicles Motorcycles
			Bus rapid transit systems	Articulated buses
			Conventional transit bus systems	Small buses Medium buses
			Taxis	Light-duty vehicles
			Non-motorized	n/a
		Interurban	Conventional transit bus systems	Small buses Medium buses
	Freight	Urban Interurban	n/a	Light-duty trucks Medium-duty trucks Heavy-duty trucks
Aviation Waterborne Rail	Passenger and freight	Urban and interurban	n/a	n/a

n/a: not applicable.

scenario, we account for differences in costs and total emissions. This study is for the period from 2010 to 2050 and emphasizes the years 2010–2030, which is consistent with the scope of the NDC.

Road transport is divided by the type of service for passengers and freight; each of those is studied in two groups, which are based on scale (urban and interurban). Urban road passenger transport is classified into five modes; different types of vehicles compose each mode. Non-road segments, including aviation, waterborne and rail segments, are grouped and modeled together (see Table 1).

Due to its high contribution to net energy consumption and transportation-related GHG emissions, the road segment was the focus of our analysis, and we modeled this segment in greater detail. Road passenger transport is characterized in terms of demand (trips), modal share, activity (vehicle kilometers) and type of fleet (age, fuel, size of vehicle and fuel efficiency). Similarly, the variables for characterizing road freight transportation include the demand (ton-kilometers) and share by type of truck (fuel, size, age and fuel efficiency). Non-road segments are represented by their net energy demand by type of fuel.

3.1. Transport demand

The transport demand is estimated based on the economic and population data. Table 2 summarizes the methods used to calculate the demand by type of segment and service. Similar to previous studies (Rentziou et al., 2012; Timilsina and Shrestha, 2009; Wang et al., 2017), road passenger transportation demand is modeled as a function of population and per capita income growth. The relationship between income and the response in travel demand is modeled via mobilization rates. These rates are estimated with a logarithmic function under the assumption of the existence of a saturation level, which is consistent with previous reports (Schafer and Victor, 2000) (see Appendix A). The net travel demand is estimated by multiplying the obtained per capita trip rate by the size of the population.

Road freight transportation demand is modeled as a function of gross domestic product (GDP) in accordance with the relationship between economic growth and cargo transport activity (Carrara and Longden, 2016; Kamakaté and Schipper, 2009; Yao et al., 2015). For non-road segments, the same assumption applies.

3.2. Modal split assumptions

Within urban passenger transportation, the model considers trips in car ($T_{c\ i}$), motorcycle ($T_{m\ i}$), public transit ($T_{p\ i}$), taxi ($T_{x\ i}$) and non-motorized ($T_{n\ i}$) modes. The total number of trips ($T_{dmd\ i}$) is the sum of these options.

The calculations for the future modal share are based on a set of assumptions defined by stakeholders (see Section 3.6). The use of cars and motorcycles is assumed to increase proportionally as the annual motorization rate increases (see Section 3.3). The quantity of trips by these modes is calculated according to Eq. (1), in which the number of vehicles ($V_{stock\ i,j}$), average rate of daily trips observed for those who own a car or a motorcycle (t_j) and average occupancy of the vehicles (o_j) are factors.

$$t_{dmd\ i,j} = V_{stock\ i,j} \cdot t_j \cdot o_j^{-1} \quad (1)$$

The share of taxis in urban trips is kept fixed and equal to the 2015 value. This value represents the limit to the fleet growth and the use of the fleet mentioned in Section 2. The number of trips in non-motorized modes is assumed to be constant at the 2015 value, and consequently, its relative proportion of the total trips decreases as time progresses.[2]

Regarding public transport, both types of systems currently in place are modeled. We consider in the BAU scenario the goal of 40% of coverage by BRT systems and non-motorized modes mentioned in Section 2. The aggregate proportion of public transport systems is the proportion remaining after subtracting the trips in other modes from the total number of urban trips. For interurban passenger transportation and freight transport, a fixed modal share equal to the baseline year is assumed throughout the scope of analysis.

3.3. Fleet characterization

The size of the stock for private modes depends on motorization rates. We estimate different rates for automobiles and motorcycles using a Gompertz function in accordance with the methods of Dargay et al. (2007) (see Eq. (2)).

$$V_{t\ i,j} = \gamma_j \cdot \theta_j \cdot Exp^{\alpha_j \cdot e^{\beta_j \cdot GDP_i}} + (1-\theta_j) \cdot v_{i-1,j} \quad (2)$$

In Eq. (2), the motorization rate per year ($V_{t,i,j}$) represents the number of vehicles per 1000 inhabitants. For the saturation level (γ_j), we assume the same value as that observed in the wealthier segments of the local population, which is 600 vehicles per 1000 inhabitants (GB, 2014). The time lag between the point at which people can afford a vehicle and the response in motorization is represented by θ_j. The parameters α_j and β_j define the curvature of the function and are calibrated with historical data on income and motorization (see Appendix A). The size of the fleet $V_{stock\ i,j}$ is estimated with the motorization rate and the size of the population (P_i) (Eq. (3)).

$$V_{stock\ i,j} = V_{t\ i,j} \cdot P_i \quad (3)$$

The size of the annual fleet for taxis and public transit systems is estimated using the number of trips, average occupancy rates and trip

[2] The 2011–2016 reports from the citizen survey "Informe de calidad de vida" (RCCV, 2016) indicate that the number of non-motorized trips have decreased in the last five years in six of eight cities studied and have remained constant in the other two cities. This survey covers large- and medium-sized cities.

Table 2
Demand drivers by segment.

Segment/type of service	Scale	Variable estimated	Macroeconomic variable employed	Function
Road/passenger	Urban	Travel demand per capita	GDP per capita	$P_{dmd\ i} = e \cdot \ln(x_i) - d$ $P_{dmd\ i}$ is the rate of trips per person per day; x_i is the monthly income per capita; e and d are parameters of the function. Values for e and d are those estimated in Acevedo et.al (2009).
	Urban	Net travel demand	Population	$T_{dmd\ i} = P_i \cdot P_{dmd\ i}$ $T_{dmd\ i}$ is the total travel demand per day; P_i is the size of the population.
	Interurban	Net travel demand	GDP and population	$T_{int\ i} = T_{int\ i-1} \cdot (1 + R_{Tdmd\ i})$ The resulting annual growth rate of T_{dmd} is represented by $R_{Tdmd\ i}$, which is employed to estimate the interurban travel demand $T_{int\ i}$.
Road/freight	Urban and Interurban	Road freight volume	GDP	$F_{vol\ i} = F_{vol\ i-1} \cdot (1 + R_{GDP\ i})$ $F_{vol,\ i}$ is the road freight volume per year; $R_{GDP\ i}$ is the GDP grow rate in the period.
Aviation, waterborne, rail	n/a	Net energy demand	GDP	$D_{j,f,i} = D_{j,f,\ i-1} \cdot (1 + R_{GDP\ i})$ $D_{j,f,i}$ is the net energy demanded per type of fuel per segment; $R_{GDP\ i}$ is the GDP grow rate in the period.

n/a: not applicable.

rates for this segment (see Eq. (1)). The size of the freight fleet by size of truck ($V_{f\ i,k}$) depends on the activity ($F_{vol\ i,k}$) and the historical load factors ($l_{f\ k}$) (Eq. (4)). No improvement in the efficiency in terms of load capacity is considered in the BAU scenario.

$$V_{f\ i,k} = F_{vol\ i,k} \cdot l_{f\ k}^{-1} \tag{4}$$

The BAU scenario considers the application of a freight fleet scrapping policy, and by means of financial incentives to retire 3000 old trucks each year for the next 5 years, this scenario aims to reduce the size of the fleet (see Section 2). With the size of the stock per segment per year and in accordance with vehicle survival rates ($S_{r\ m,a}$), we estimate the quantity of new vehicles per year ($V_{new\ i,m}$) according to Eq. (5).

$$V_{new\ i,m} = V_{stock\ i,m} - \sum (S_{r\ m,a} \cdot V_{i,m}) \tag{5}$$

3.4. Energy demand and emissions estimation

The BAU scenario is conservative in terms of new technologies and fuel switching. The fuel share remains constant and equal to that in baseline year throughout the scope of analysis (see Table 3). In terms of technology, an annual improvement in fuel efficiency (1%) of new vehicles is assumed.

CO_{2eq} emissions are estimated on an annual basis in accordance with bottom-up methodology. Emissions by the road segment are calculated according to Eq. (6).

$$CO_{2eq\ i} = \sum_{j,f,k} (Ns_{i,j} \cdot \chi_{i,j,f,k} \cdot A_{i,j,f,k} \cdot E_{i,j,f,k} \cdot EC_f \cdot EF_f) \tag{6}$$

CO_{2eq} emissions from i are a function of the size of the fleet ($Ns_{i,j}$) for each mode j, the share of the fleet by type of fuel f and type of vehicle k ($\chi_{i,j,f,k}$), the activity ($A_{i,j,f,k}$), the fuel efficiency by type of vehicle ($E_{i,j,k,f}$), the energy content by type of fuel (EC_f) and the CO_{2eq} emission factor (EF_f) by type of fuel. The CO_{2eq} emission factor is estimated based on IPCC default fuel-based emission factors for carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). The equivalent values for CH_4 and N_2O to CO_2 are based on their 100-year global warming potential, as indicated in the 2006 IPCC Guidelines for National GHG Inventories (Maurice et al., 2006).

Emissions by non-road segments are calculated based on their net energy usage (Eq. (7)). These emissions depend on the fuel demand in volume by segment ($d_{i,j,f}$), the energy content per type of fuel (EC_f) and the CO_{2eq} emission factor (EF_f).

$$CO_{2eq\ i} = \sum_{j,f} d_{i,j,f} \cdot EC_f \cdot EF_f \tag{7}$$

Table 3
Fuel share in the baseline year in road segment.

Type of service	Scale	Type of vehicles	Fuel share (percentage)		
			Diesel	Petrol	Natural gas
Passenger	Urban	Light duty vehicles	17	58	25
		Motorcycles	0	100	0
		Taxis	0	60	40
		BRT buses	100	0	0
		Conventional buses	80	10	10
	Interurban	Buses	100	0	0
Freight	Urban	Light-duty trucks	39	55	6
		Medium-duty trucks	39	55	6
		Heavy-duty trucks	100	0	0
	Interurban	Light-duty trucks	89	10	1
		Medium-duty trucks	89	10	1
		Heavy-duty trucks	100	0	0

3.5. Analysis of mitigation options

3.5.1. Selection of mitigation options

We use an expert-based method within the marginal abatement cost analyses approach. As such, we assess previously selected individual actions (see Section 3.6) rather than model-derived options (e.g., optimization models). From the readily available options in the market, 20 actions were selected to establish a possible low-carbon pathway for Colombian transportation. Different types of instruments were considered. Within the policy instruments, we include green driving programs, traffic demand instruments (e.g., congestion charging), fuel efficiency standards and limits on maximum age. Regarding the technological abatement options, we include hybrid vehicles, electric vehicles and fuel substitution in different segments. Finally, in the group of non-technological options, the alternatives include the implementation of public bicycle systems, programs to encourage the accelerated retirement of older trucks, and intermodal freight transport alternatives. Table 4 summarizes the mitigation actions considered in this study. A gradual implementation is assumed for all of them, but the pace of adoption varies by segment.

3.5.2. Methodology to assess mitigation options

We use a financial-technical costing approach to assess mitigation actions (see Eqs. 8–10). The incremental cost of implementing a mitigation action (C_a) is estimated as the difference between the cost of a segment in the BAU scenario ($c_{m,BAU}$) and the cost of the same segment when a mitigation action is applied ($c_{m,\ a}$). The costs consider the capital costs ($c_{inv,i}$) and both the operation and maintenance costs ($c_{om,i}$). A discount rate (d) of 10% (in U.S. dollars [US$]) is used for consistency

Table 4
Description of the mitigation actions.

Mitigation action	Segment	Starting date	Description
Fuel efficiency standards	Transit buses in big cities	2020	New vehicles are 30% more efficient. The fleet renovation rate is the same than that at the baseline.
	Interurban buses	2020	
Green driving programs and fuel efficiency standards	Transit buses in small and medium cities	2020	New vehicles are 30% more efficient. Green driving practices lead to an additional reduction in 10% of the fuel consumption per unit distance. The fleet renovation rate is the same than that at the baseline.
	Private vehicles	2025	
	Taxis	2025	
Road charging	Private vehicles	2020	The implementation of a congestion charge in the Central-Business-District in the capital according to the local study by Tyler et al., (2013).
Hybrid vehicles	Taxis	2020	Substitution of 30% of the fleet in 2050 by hybrid vehicles (petrol-electricity). By 2030, there are 42,000 hybrid taxis.
	Private vehicles	2023	Substitution of 25% of the fleet in 2050 by hybrid vehicles (petrol-electricity). By 2030, there are 3000 vehicles substituted.
Electric vehicles	Taxis	2020	Substitution of 20% of the fleet in 2050. By 2030, there are 36,000 electric vehicles.
	Conventional buses, big cities	2023	Substitution of 50% of the fleet in 2050. By 2030, there are 6000 electric buses.
	Conventional buses, small and medium cities	2023	Substitution of 30% of the fleet in 2050. By 2030, there are 11,600 electric buses.
	Private vehicles	2023	Substitution of 30% of the fleet in 2050. By 2030, there are 57,000 electric vehicles in the stock.
	BRT buses	2023	Substitution of 75% of the fleet in 2050. By 2030, there are 1000 electric buses.
Fuel substitution	Freight	2025	Substitution of diesel by compressed natural gas in 15% of the fleet.
	Freight	2025	Substitution of diesel by liquefied natural gas in 15% of the fleet.
Public bicycle systems	Big cities	2021	Trips in bicycles in the eight biggest cities reach a participation of 4%.
Reduction of oversupply	Freight	2024	The 3000 older trucks are retired each year. This is the continuation of a current program set by the government.
Limits on maximum age	Freight	2020	Replace the trucks older than 30 years.
Intermodal transport	Freight	2030	Substitute road transportation by a combination road-waterborne to transport 16 million tons of products through the Magdalena river (main river in the country). It starts with 10 million tons in 2030.
	Freight	2030	Substitute road transportation by a combination road-rail to transport 40 million tons of mining products. It starts with 20 million tons in 2030.

with the Colombian National Planning Department guidelines for the analysis related to the Colombian Low Carbon Development Strategy (CLCDS). Emissions avoided represent the difference between the emissions in a segment in the BAU scenario ($CO_{2eq\ m,BAU}$) and those in the mitigation scenario ($CO_{2eq\ m,\ a}$).

$$C_a = \sum_i (c_{m,\ a} - c_{m,BAU}) \tag{8}$$

$$c_{m,i} = (c_{inv,i} + c_{om,i})/(1 + d)^t \tag{9}$$

$$CO_{2eq\ a} = \sum_i (CO_{2eq\ m,BAU} - CO_{2eq\ m,\ a}) \tag{10}$$

The actions related to electric mobility are evaluated with the Model for Economic and Environmental Assessment of Electric Vehicles (Meave) (Delgado et al., 2014), which is designed to analyze options in the Colombian transport sector. The GHG abatement potential for electric mobility actions accounts for the average CO_{2eq} emission factor from the generation of electricity in Colombia (175 g/kWh). In addition, as the model allows for co-benefit estimations, benefits in terms of health effects due to reductions in particulate matter emissions are calculated for this set of actions. Health benefits are presented separately and are not included within the net cost of these actions to make their results comparable with those of other actions.

3.6. Participatory approach

The scenarios used in the analysis to design the CLCDS were established following an inclusive methodology established under the Mitigation Actions, Plans and Scenarios (MAPS) program (Maps, 2017). Scenario-building teams (SBTs) were confirmed by experts from NGOs, community groups, and government and private entities, all of whom were invited by the Ministry of Environment. Eight meetings attended by more than two hundred people occurred between 2012 and 2016; these meetings were held to discuss the assumptions of the scenarios involving the different sectors, including the transportation scenarios presented in this study. A description of this process is reported by Raubenheimer et al. (2015) and MADS (2015).

3.7. Uncertainty and limitations

The BAU scenario intends to represent what stakeholders consider the most likely scenario. A limitation of this approach is the allocation of the transport demand within different modes and types of vehicles, as this approach does not account for the response of consumers to factors such as the cost of the different options to travel. Nevertheless, this method is common among both energy-economic-environment models and bottom-up simulation models (Fulton et al., 2009; Mittal et al., 2016).

A similar limitation exists concerning the method for estimating the costs and emissions of the mitigation actions, as the approach used does not consider market responses or behavioral changes. Therefore, the technical mitigation potential estimated here is probably higher than the economic potential. For instance, due to the rebound effect, it is expected that some of the savings in emissions will be outpaced by new induced consumption or even overcome by consumption in more carbon-intensive sectors (backfire effect) (Druckman et al., 2011). In addition, the green paradox effect and leakage (spatial and inter-temporal) are likely to reduce the GHG abatement potential estimated for the transport sector (Eliasson and Proost, 2015).

The main advantage however, is the detailed characterization of the transport sector. A description of the advantages and disadvantages of this family of cost-effective methods for estimating both the costs and emissions of mitigation actions is discussed by Kok et al. (2011).

When interpreting the results, it is important to acknowledge that these methodologies cannot capture non-financial costs. As a result, what we characterize as a win-win strategy (actions that produce a return on investment) may have several barriers to overcome, which will generate additional costs (Proost and Van Dender, 2012; Taylor, 2012).

However, technical mitigation potential and costs are important

indicators. The estimations presented in this study consider the efficiency of the transport sector in Colombia; this efficiency is determined by the specific characteristics in terms of fleet and performance. We consider this analysis helpful in identifying preliminary opportunities for reducing GHG emissions.

4. Results and discussion

4.1. GHG emissions in the BAU scenario

The compound annual growth rate (CAGR) of CO_{2eq} emissions for the transport sector in Colombia is 3.89% for 2010–2030 and 3.51% for 2031–2050. These findings represent a scenario with a CARG of 3.99% for the GDP. The annual CO_{2eq} emissions in 2030 will be 48.6 Mt. Despite the relatively rapid increase in total emissions, per capita GHG emissions will remain low during the subsequent decades. Compared with those of 1.79 t per year in the European Union and 5.24 t per year in the United States in 2010 (World Energy Council, 2015), the transportation per capita emissions will increase from 0.5 t per year in 2010–0.8 t per year in 2030. This projection is consistent with previous studies reporting that per capita emissions in future scenarios are lower for developing countries than for countries with more-developed economies (Sims et al., 2014; Figueroa et al., 2013).

The contribution of freight transport (urban and interurban) to CO_{2eq} emissions is approximately 50% during the scope of analysis. Within this period, the interurban freight segment is the main contributor to GHG emissions in the transport sector. The largest change in the proportion of CO_{2eq} emissions from urban passenger modes is due to increases in private mode transportation and the subsequent decrease in public transportation (see Table 5).

4.2. Mitigation options: emissions avoided and costs

Table 6 summarizes the results for the mitigation actions with respect to emissions reductions, capital costs and net costs. The costs are expressed in 2010 US$, and negative values represent overall savings. There is potential to avoid 58.3 Mt of CO_{2eq} until 2030 if all measures are applied; this amount represents 8% of the cumulative CO_{2eq} emissions in the BAU scenario. The mitigation scenario deviates by 20% with respect to the BAU in 2030. In Fig. 2, the deviation is the accumulative potential of the application of all measures. The mitigation potential during 2010–2050 represents 18% of the cumulative emissions in the BAU. Furthermore, the mitigation portfolio does not alter the upward emissions trajectory.

The implementation of fuel economy standards and green driving represents the group of measures that exhibits the highest reduction potential; this group represents one-third of all emissions avoided in the mitigation scenario (Fig. 2). Electric mobility represents one-fifth of the mitigation potential until 2030 and increases to one-fourth during 2031–2050. Other types of actions contribute similarly to the long-term mitigation potential (13–16%).

The mitigation actions have high upfront costs. Total investments of US$6900 million and US$26,700 million will be needed until 2030 and until 2050, respectively. The net capital cost during 2010–2030 is equivalent to the total investment by the Colombian government in the transport sector in 2015 (MT, 2016). The annual investment needed in the mitigation scenario represents 0.5–0.7% of the national GDP until 2030. These costs will increase as time progresses and will reach 1.5% of the GDP in 2040 and approximately 4% of the GDP at the end of the analysis period. However, there are significant savings because of better performance of the systems and gains in energy efficiency. In the medium term (2010–2030), these savings lead to a negative net cost (-US$13 million). In the long term (until 2050), when all the actions are considered, the savings do not offset the costs of the mitigation actions.

Table 5
Share in CO_{2eq} emissions by road-transport categories in Colombia.

Categories	Share in emissions (percentage)		
	2010	2020	2030
Freight: interurban	42	41	40
Private transport: urban	20	24	31
Freight: urban	10	10	9
Public transport: interurban	10	9	7
Public transport: big cities	10	8	7
Public transport: taxis	4	4	4
Public transport: small and medium cities	3	3	2
Annual CO_{2eq} (Mt)	20	29	41

4.2.1. Importance of a long-term perspective

Fig. 3 shows the results of two groups of mitigation actions: Group 1 refers to those actions generating savings in the long term (negative net cost), and Group 2 refers to those actions with a positive net cost. For each group, cumulative results in terms of avoided emissions, capital costs and net costs are presented. The mitigation actions are organized by their capital cost in the medium term. A common characteristic of both types of measures is that the bulk of the mitigation potential is achieved toward the end of the period (see parts a and b), and the return on investment follows the same pattern, as is reflected in the net cost (parts e and f).

In the group of actions with negative net costs (Group 1 in Fig. 3), the slope becomes steeper toward the end of the curve. The actions included to this point (from a to h) generate 60% of the net mitigation potential with 14% of the net investment. Actions related to improved fuel efficiency in public modes are examples of alternatives that present relatively low capital costs (2% of the net capital costs until 2050) and high mitigation potential (one-third of the total mitigation).

Parts e and f in Fig. 3 show the impact of accounting for long-term results when the actions to be implemented in the medium term are prioritized. For example, from a financial point of view, the intermodal freight option (f-road-waterborne) is of interest if the long-term net cost (2010–2050) is considered. In the medium term (2010–2030), its capital cost is higher than the return on investment. In addition, actions such as this one help to reduce future lock-in effects, as the alternative would be the continuation of building road infrastructure. Other options favored by a long-term perspective are the freight fleet renewal program and the switch to liquefied natural gas-powered trucks.

There is another group of alternatives, including electric mobility in private modes, which are relatively expensive according to the long-run scenarios. However, there is growing evidence earlier electrification in mobility and gradual investments in infrastructure might result in lower costs (IPCC, 2012; Leibowicz, 2018; Oshiro et al., 2017). This is true for new technologies in general, and not only for electric vehicles (Comello and Reichelstein, 2017; Newbery, 2018). Lower cost are due to the possibility of avoiding aggressive substitution paths and because this allows identifying barriers and the anticipation of solutions to promote the adoption of the technologies (Corradini et al., 2018; Morganti and Browne, 2018; Oshiro et al., 2017). Also, because earlier and gradual implementation of the infrastructure is crucial in the adoption of technologies (Leibowicz, 2018). The analyses comprising longer periods allow the identification of mitigation actions for which acting earlier will reduce their net implementation costs.

These results are consistent with those of previous studies (Fraser and Chester, 2016; Oshiro et al., 2017; Shukla and Dhar, 2015) with respect to the importance of planning for the medium term while accounting for long-term objectives. The results from the assessment of the mitigation actions when only medium-term periods of analysis are considered might lead to incorrect decisions. In addition, important lock-in effects exist in transportation; consequently, the later the interventions are, the greater the inertia that must be overcome.

Table 6
Mitigation actions costs and abatement potential.

Segment	Mitigation options by segment	CO_{2eq} mitigation potential (Mt)		Capital cost (US$ million)		Net cost (US$ million)	
		2010–2030	2010–2050	2010–2030	2010–2050	2010–2030	2010–2050
Public urban	Improving fuel efficiency and green driving in conventional buses, small and medium cities	11.7	48.8	44	48	− 1272	− 2388
	Electric buses in conventional bus systems, small and medium cities	3.4	16.8	1052	5187	705	3477
	Public bicycle systems	3.3	17.0	183	218	− 92	− 413
	Electric buses in conventional systems, big cities	2.6	15.2	518	3058	0.4	2.1
	Electric taxis	2.2	10.6	218	1038	− 19	− 91
	Improving fuel efficiency in conventional buses, big cities	2.0	8.5	19	21	− 195	− 377
	Hybrid taxis (petrol - electricity)	2.0	11.6	265	1534	− 75	− 436
	Electric buses in bus rapid transit systems	0.9	8.9	105	991	53	503
	Improving fuel efficiency in taxis	0.4	7.1	11	27	− 22	− 208
Public interurban	Improving fuel efficiency in interurban buses	2.8	18.7	17	27	− 293	− 767
Private transport	Improving fuel efficiency and green driving in light duty vehicles	2.3	48.9	653	1805	446	109
	Congestion charges in the capital city	0.8	3.5	44	44	− 16	− 99
	Electric vehicles	0.1	37.5	11	4262	6	2411
	Hybrid vehicles	0.0	17.6	1	3458	1	2593
Freight transport	Fleet renewal program	7.6	36.8	1123	1380	308	− 353
	Liquefied natural gas trucks	7.1	43.4	1288	1653	310	− 1005
	Reduction of oversupply	4.6	35.8	83	136	− 655	− 2110
	Compressed natural gas trucks	3.7	25.9	1232	1581	779	244
	Intermodal transport: road - waterborne	0.6	26.0	50	124	4	− 591
	Intermodal transport: road - rail	0.3	10.7	12	194	14	137
Total		58.4	449	6931	26,787	− 13	638

4.2.2. GHG mitigation in urban passenger transportation

In the BAU scenario, the carbon intensity of an average trip increases as time progresses, despite efficiency improvements to the new fleet. The average fuel economy increases by 9% between 2010 and 2030. However, due to changes in modal distribution (Fig. 4), the average carbon intensity, referring to the annual emissions of a representative trip increases from 172 kg CO_{2eq} in 2010–257 kg CO_{2eq} in 2030. While travel demand grows at a CAGR of 2.3%, emissions generated by those trips increase by 4.4% per year (Fig. 5).

In 2010, 54% of net urban trips involved the use of public transport systems (including taxis). Under the BAU scenario, this share decreases to 30% in 2030. This finding means that the capacity of public transport systems according to government plans for subsequent years (DNP, 2015b) might be greater than the demand. This phenomenon is already occurring in several cities nationwide, where private transportation and informal modes are attracting demand from the public transport systems; consequently, public modes are being used under the installed capacity (DNP, 2014b).

Compared with the BAU scenario, the mitigation measures for urban transportation scenario results in a 25% improvement in terms of the annual CO_{2eq} per passenger trip in 2030. The effect of the GHG mitigation actions in 2030 is equal to the return of the carbon intensity per trip in 2016. The mitigation pathway, which mainly comprises technological options, will reverse the effect of 14 years of modal shift toward private modes. The analyzed actions are not sufficient to ultimately reach the 2010 carbon intensity, which corresponds to basic technologies but a more efficient modal distribution in terms of carbon emissions. As reported previously, GHG mitigation is maximized when policies involving travel demand management, efficient modal distribution, and cleaner technologies are integrated (Figueroa et al., 2013; Cuenot et al., 2012; Sweeting and Winfield, 2012).

The results of the analysis conducted in terms of city size and type of public transportation show that some options become financially feasible when certain conditions are met. As expected, the investment costs related to electric transportation are recovered faster when those transportation methods replace highly inefficient fleets or vehicles traveling relatively great distances. Electric vehicles are financially suitable for taxis but not for private vehicles, as the activity of the former is four to five times greater than the average activity of private cars. Likewise, from a financial perspective, electric buses in the conventional public transit system provide better outcomes in large cities than in small- and medium-sized cities. These results represent the

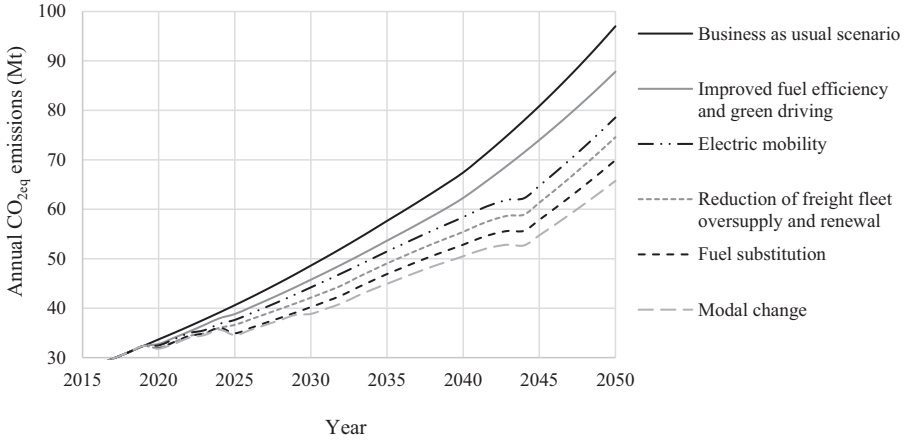

Fig. 2. Mitigation potential by type of measure. NOTE: In Fig. 2 the line corresponding to each group of actions is the incremental mitigation potential with respect to the group of measures above of it. Therefore, the emission pathway represented by the last group of actions in the graph (modal change) also represents the mitigation scenario, when all the measures are included.

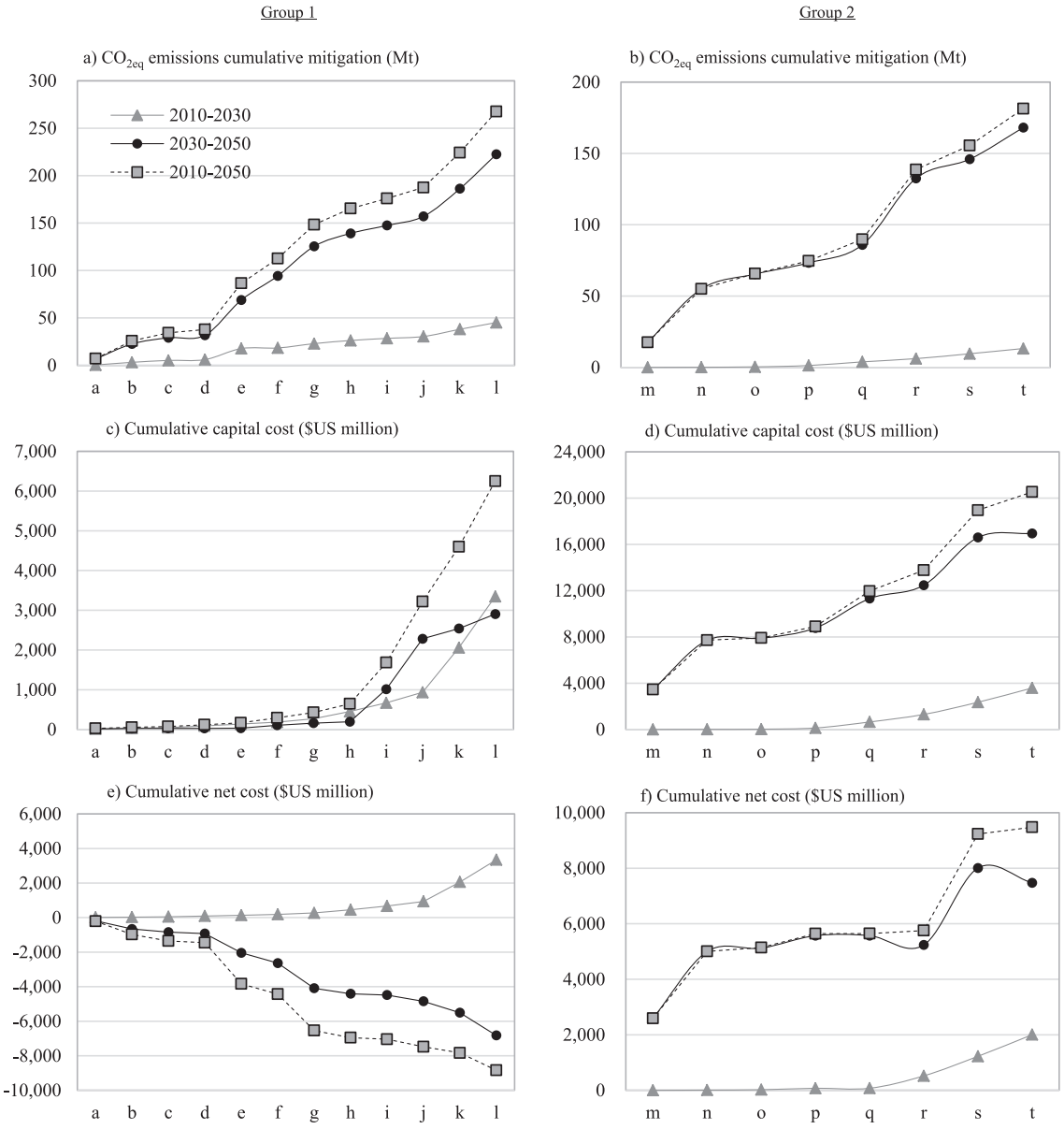

Fig. 3. Mitigation actions and results for the periods 2010–2030 and 2010–2050. NOTE: Group 1: mitigation actions with negative net cost (generating savings) in the period 2010–2050. Group 2: mitigation actions with positive net cost in the period 2010–2050. See Table 4 for a description of the mitigation actions and Table 6 on the costs and mitigation potential. a) improving fuel efficiency in taxis, b) improving fuel efficiency in interurban buses, c) improving fuel efficiency in conventional buses in big cities, d) congestion charges in the capital city, e) improving fuel efficiency and green driving in conventional buses in small and medium cities, f) intermodal transport: road - waterborne, g) reduction of oversupply in freight fleet, h) public bicycle systems, i) electric taxis, j) hybrid taxis, k) freight fleet renewal program, l) liquefied natural gas trucks, m) hybrid private vehicles, n) electric private vehicles, o) intermodal transport: road - rail, p) electric buses in bus rapid transit systems, q) electric buses in conventional systems in big cities, r) improving fuel efficiency and green driving in light duty vehicles, s) electric buses in conventional bus systems in small and medium cities, t) compressed natural gas trucks.

specific characteristics considered for the fleet in the baseline and alternative options.

Owing to their reduction in emissions of particulate matter in urban areas, the electric mobility options lead to health benefits that amount to US$1490 million through 2050. The largest portion of the health benefits comes from replacing heavy-duty diesel vehicles. The substitution of conventional buses with electric vehicles in large cities becomes cost efficient (negative net cost) if the co-benefits in terms of air quality are included in the monetary assessment. Although the co-benefits in health from the substitution of buses from small- and medium-sized cities and BRT systems are significant, these benefits are lower than the financial costs of implementing those mitigation actions.

The results show that fuel efficiency alternatives are suitable for public transportation regardless of the type of system and the size of the city. Compared with the BAU scenario, these options result in a 30% improvement in fleet fuel economy (Table 4). This goal is still conservative according to global projections, as the potential for fuel consumption reductions for heavy-duty vehicles in different regions of the world has been estimated to range from 30% to 50% (ICCT, 2016). As mentioned previously, a high proportion of the current fleet is old; therefore, compared with that of global benchmarks, the specific fuel consumption for those vehicles is relatively high (ICCT, 2016).

4.2.3. Potential to avoid emissions in freight transportation

In the BAU scenario, the scrapping program and the improved fuel efficiency of new trucks improve the performance of the cargo fleet. The

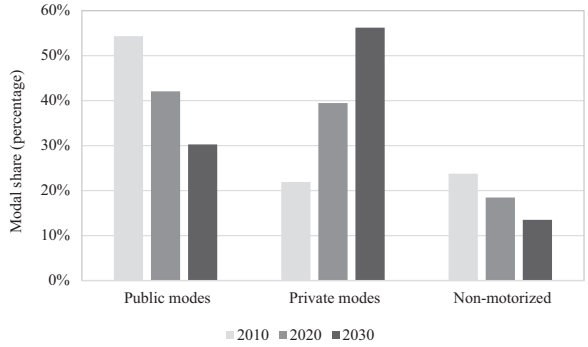

Fig. 4. Modal share in passenger urban trips. NOTE: *Baseline year 2010: estimated according to data from 11 cities. It represents the principal mode people use to commute.

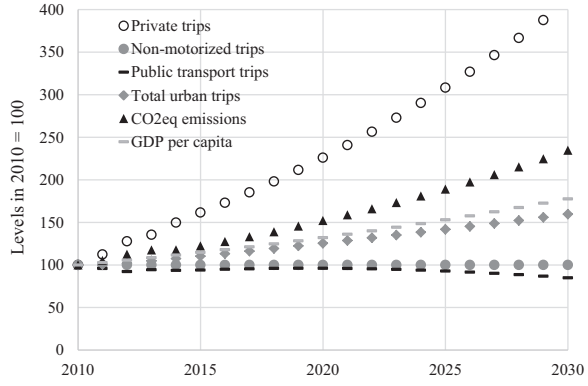

Fig. 5. Relative growth in urban transportation demand and CO_{2eq} emissions.

average carbon intensity decreases from 722 g CO_{2eq}/km in 2010–674 g CO_{2eq}/km in 2030. However, this does not compensate for the increase in the activity, which doubles within the same period. The fuel efficiency of new vehicles improves by 22% between 2010 and 2030, but the effect on the average fleet efficiency is an improvement of 6%.

The net mitigation potential for the freight segment represents 40% of the cumulative emissions in the BAU until 2050. If 2010–2050 is considered, the mitigation actions in freight transport generate returns outweighing the net investment. Intermodal transportation represents 20% of the freight mitigation potential. Nonetheless, local studies have identified the potential for implementing multimodal options in at least four additional corridors throughout the country (MME, 2011; MT, 2017b; Roda and Perdomo, 2011). Most of the mitigation potential within freight transport corresponds to actions aimed at reorganizing the system: programs to retire old vehicles, better use of the capacity and intermodal options. The potential of this group of actions reaches 60% through 2050.

Under the current conditions of renewal and scrap fees, it will take 40 years to renovate the entire freight fleet. Efforts directed to new vehicles entering the fleet will have a minor effect on reducing CO_{2eq} emissions in the medium term. Therefore, to achieve significant GHG reductions by means of technological actions, intervening the stock will be necessary.

4.3. Lessons from the public participatory approach

The public participatory approach provided valuable inputs for the analysis presented here. This approach plays an important role in policymaking in GHG mitigation and helps resolve drawbacks inherent to marginal abatement cost approaches (Ibrahim and Kennedy, 2016; Kesicki and Strachan, 2011). This approach was conducted under the MAPS initiative; thus, experts were asked to think more in terms of co-benefits in GHG mitigation from current policies rather than in ways to meet a specific carbon reduction goal. As a means to achieve other strategic objectives, green growth is common in developing countries (Zimmer et al., 2015). However, in terms of results, these two approaches generate different outcomes. From a co-benefit perspective, the mitigation pathway often leads to a smaller deviation from the BAU scenario, as the mitigation potential is an indirect result and not an objective. However, from a decarbonization approach, the goal in GHG reduction is an input (Ribera and Sachs, 2015) whose estimate is consistent with required scientific scenarios to reach the global goal of maintaining temperature increases well below 2 °C with respect to preindustrial levels (Schleussner et al., 2016).

Most likely because of the methodology, the alternatives suggested by the experts who participated in the SBT meetings generally lack proposals on structural changes to the current methods of transporting people and goods across the country. However, this fact might also be considered a reflection of lock-in effects in institutional and behavioral aspects (Seto et al., 2016), reinforcing the inertia of GHG emissions. This area deserves further attention in local transportation analyses.

Importantly, this process created for the first time in the country a space for discussing GHG mitigation among stakeholders from different sectors. Important to future processes is the interest of the transportation discussion participants, who expressed their involvement throughout the process. This response was not always the same as that in other sectors (Uniandes and Minambiente, 2014).

5. Consistency of climate policy with transport, energy and environmental policies

Similar to that reported for other developing countries (Dulal and Akbar, 2013; Figueroa et al., 2013; Shukla and Dhar, 2015; Zimmer et al., 2015), compared with the mitigation of climate change emissions, the perception of more pressing problems was a greater concern during the SBT meetings. In this context, given the interactions between transportation and other sectors, the identification of strategies in which interests of the different sectors converge can help to promote actions that are beneficial for multiple purposes. We emphasize three aspects in which GHG mitigation strategies in the transport sector may work as a mechanism to integrate and catalyze the objectives of other sectors.

5.1. GHG mitigation and air quality

As presented in Section 4.2.2., the use of alternative technologies results in important health benefits from decreased local pollutant emissions. In addition, the policies headed by the transport sector to promote public transit and non-motorized modes (DNP, 2015b) need to consider air quality conditions. Local studies have reported high concentrations of local pollutants in transport-related microenvironments (Behrentz and Espinosa, 2011; Morales-Betancourt et al., 2017), particularly inside the cabins of public transit buses and near major roads; with respect to the latter, people walking and biking are most affected.

5.2. Incorporation of renewable sources in the national electric system

The incorporation of wind and solar sources to the electric generation system is desirable for reducing the vulnerability of a highly dependent hydro system and for lowering generation costs (UPME, 2015c). Potential projects involving renewable generation have been identified (UPME, 2016), and fiscal incentives related to their installation exist. However, low electricity demand is a current barrier to new projects. The transport sector, which is the greatest energy-consuming sector in Colombia, offers opportunities for electric transport systems, particularly public transportation (e.g., railways, subways and high-speed trains). The electricity demand in the mitigation scenario reaches 1.4 TWh in 2030 and 6.17 TWh in 2050.

5.3. GHG mitigation and urban transportation goals

In Section 4.2.2, we explained that a high proportion of public transportation in the modal share is important to attain low-carbon trips. From the transportation perspective, the promotion of public transit represents a method to reduce congestion, which is the major externality generated by urban transportation in Colombian cities (DNP, 2016). In addition, improving public transport systems represents a way to tackle the increase in the use of automobiles and motorcycles and the externalities related to them, such as increasing accident rates (Jimenez et al., 2015), increasing informality in transportation (Oviedo Hernandez and Titheridge, 2016) and worsening air pollution (SDA, 2010).

6. Conclusions and policy implications

In this study, we estimate GHG emissions generated by the Colombian transport sector. Under the BAU scenario, CO_{2eq} emissions will increase twofold between 2010 and 2030 and will quadruple through 2050. In the mitigation scenario, the application of all actions can potentially avoid 8% of the emissions accumulated through 2030 and 18% through 2050. The results of the carbon intensity show that maintaining a high proportion of public transit systems with fleets equipped with current technologies for urban traveling is more effective than implementing all the technological options if private modes become the dominant method of travel. Likewise, the actions aimed at reorganizing freight transportation systems are as important as the technological alternatives affecting the fleet. The former represents the majority of the potential for avoiding GHG emissions in this segment in the long term.

The capital costs of reducing GHG emissions in the Colombian transport sector are high and might be the main barrier to the implementation. Nonetheless, mitigation actions exist in which the return outpaces the investment (e.g., fuel efficiency standards, public bicycle systems, switching to natural gas vehicles for freight transport). Additionally, there are mitigation actions that contribute to achieving objectives regarding urban air quality, incorporating renewable sources in the electricity generation system and reducing externalities from urban transportation (e.g., congestion and accidents).

There are multiple mitigation actions not included in this study. These actions range from new technologies such as electric waterborne transport to multisector actions such as those related to land-use policies; these technologies need to be considered in future analyses of the country, mainly in the segments where the options analyzed in this study still result in very high application costs.

In terms of planning, as the implementation of the mitigation actions will require coordination across multiple sectors, the reduction in institutional and behavioral lock-in effects will require additional attention in the strategies toward low-carbon transport systems. Results highlight the importance of performing analyses comprising longer periods, to identify mitigation actions for which acting earlier might help in overcoming barriers and thus to reduce their future implementation costs. This supposition is important when considering that long-term planning is a relatively recent practice in national institutions and is still not common with respect to transportation policy making across the developing world.

The results from technical models such as the one presented here need to be accompanied by other exercises. One exercise involves having a broader picture of the transport actions within the energy sector, interactions with land-use policies and analyses of mechanisms to implement the mitigation actions.

Acknowledgments

The authors would like to thank the team from the Ministry of Environment, which led the initiative. We express our gratefulness to the MAPS program, which led the participatory process to design the CLCDS and provided technical and financial support to this process.

Funding

This study was developed by the Universidad de los Andes for the Colombian Ministry of Environment and Sustainable Development within the framework of the CLCDS. The Colombian Administrative Department of Science, Technology, and Innovation – Colciencias (Con. 528/2011), FONADE (Contract 2112394), the United Nations Development Program (Contract 0000018768) and the World Bank (Contract 7173727) supported this work.

Disclaimer

The opinions, findings and conclusions presented here are of the authors and do not necessarily represent those of the Colombian government agencies or the funding organizations.

Appendix A. Model calibration and validation

Motorization rates estimation

The calibration was performed following an iterative process, using the least square method to find the parameters that minimize the difference between the historical motorization rates and the estimated rates for a given value of GDP per capita. The calibration parameters are θ, α,and β (see

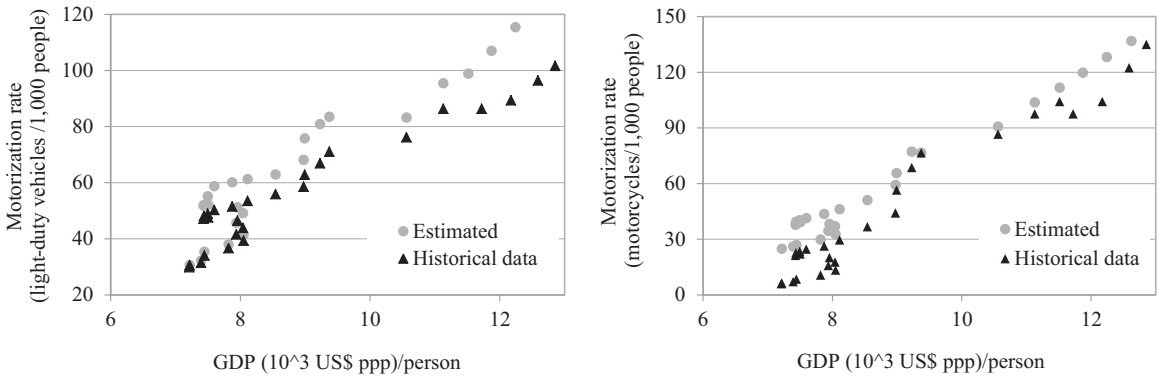

Fig. A.1. Motorization rate functions: light-duty vehicles and motorcycles.

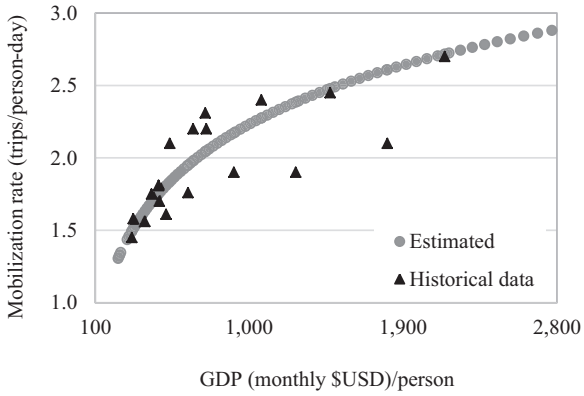

Fig. A.2. Mobilization rate function.

Section 3). Parameter ranges for similar countries are provided in the analysis by Dargay et al. (2007). The historical data employed in the calibration correspond to the period between 1990 and 2010. The function to estimate the motorization rate in the period 2010–2050 utilizes a saturation rate of 700 vehicles per 1000, as defined in the SBTs. The set of parameters are those obtained for 2010, which is the last year in the calibration dataset. We used different calibration parameters for light-duty vehicles and motorcycles. In Fig. A.1 we present the estimated and historical motorization rates.

Mobilization rate estimation

The parameters of the mobilization rate function were obtained from a previous study (Acevedo et al., 2009), where authors calibrated the function employing historical data from Colombia and similar countries in South America. The mobilization rates predicted by the model reasonably fit the data reported in recent mobility surveys for Colombian cities, showing differences between 1% and 20%. The comparison is presented in Fig. A.2.

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